

**STUDY OF NUCLEAR EFFECTS IN THE INCLUSIVE
NEUTRINOPRODUCTION OF $\Delta^{++}(1232)$**

N.M. Agababyan¹, N. Grigoryan², H. Gulkanyan²,
A.A. Ivanilov³, V.A. Korotkov³

¹ Joint Institute for Nuclear Research, Dubna, Russia

² Alikhanyan National Scientific Laboratory
(Yerevan Physics Institute), Armenia

³ Institute for High Energy Physics, Protvino, Russia

Abstract

For the first time, the inclusive neutrino production of $\Delta^{++}(1232)$ from nuclei is investigated. The total yield of $\Delta^{++}(1232)$ in neutrino-nuclear interaction is found to be $\langle n \rangle_{\nu A} = 0.080 \pm 0.011$, being compatible with $\langle n \rangle_{\nu N} = 0.091 \pm 0.013$ inferred for neutrino-nucleon interactions. It is shown that the $\Delta^{++}(1232)$ inclusive spectra on variables x_F , z and the isobar total momentum for νA interactions are shifted toward lower values respective to those for νN interactions, that can be caused by secondary intranuclear collision processes. No indication on a significant nuclear absorption of $\Delta^{++}(1232)$ leading to its disappearance is found.

1. INTRODUCTION

Experimental investigations of the leptonproduction of hadronic resonances on nuclei are necessary for a deeper insight into the space-time structure of the quark string fragmentation and the formation of hadrons, a significant fraction of which originates from the resonance decays (see [1] and references therein). At present, the experimental data concerning the nuclear medium influence on the inclusive neutrino production of resonances are rather scarce and concern only mesonic resonances (see e.g. [2, 3] concerning ρ mesons), while no data concerning baryonic resonances are available.

The aim of this work is to obtain the first experimental data on the $\Delta^{++}(1232)$ inclusive neutrino production from nuclear targets, providing an information about nuclear effects in this process. In Section 2, the experimental procedure is described. The experimental results are presented in Section 3 and summarized in Section 4.

2. EXPERIMENTAL PROCEDURE

The experiment was performed with SKAT bubble chamber [4], exposed to a wideband neutrino beam obtained with a 70 GeV primary protons from the Serpukhov accelerator. The chamber was filled with a propane-freon mixture containing 87 vol% propane (C_3H_8) and 13 vol% freon (CF_3Br) with the percentage of nuclei H:C:F:Br = 67.9:26.8:4.0:1.3 %. A 20 kG uniform magnetic field was provided within the operating chamber volume.

Charged-current interactions containing a negative muon with momentum $p_\mu > 0.5$ GeV/c were selected. The overwhelming part of protons with momentum below 0.6 GeV/c and a fraction of protons with momentum 0.6-0.85 GeV/c were identified by their stopping in the chamber. Stopping π^+ mesons were identified by their $\pi^+-\mu^+-e^+$ decay. A fraction of low-momentum ($p_{\pi^+} < 0.5$ GeV/c) π^+ mesons were identified by the mass-dependent fit provided that the χ^2 -value for the pion hypothesis was significantly smaller as compared to that for proton. Non-identified positively charged hadrons are assigned the pion mass or, in the cases explained below, the proton mass. It was required the errors in measuring the momenta be less than 24% for muon, 60% for other charged particles and V^0 's (corresponding to neutral strange particles) and less than 100% for photons. The mean relative error ($\Delta p/p$) in the momentum measurement for muons, pions, protons and gammas was, respectively, 3%, 6.5%, 10% and 19%. Each event was given a weight to correct for the fraction of events excluded due to improperly reconstruction. More details concerning the experimental procedure, in particular, the reconstruction of the neutrino energy E_ν , can be found in our previous publications [5, 6].

The events with $3 < E_\nu < 30$ GeV were accepted. The total number of accepted events was 8390, with the mean value of the neutrino energy $\langle E_\nu \rangle = 8.7$ GeV. Below we will study (and compare) the inclusive $\Delta^{++}(1232)$ production in two subsamples of events: the quasinucleon subsample (B_N) and nuclear subsample (B_A) which are composed as described below (see for details [6, 7]). The subsample B_N includes the events without any indication of the nuclear disintegration or a secondary intranuclear interaction, satisfying the following topological and kinematic criteria: the net charge of secondary hadrons was equal to +1 (for quasinucleon subsample B_N) or +2 (for quasinucleon subsample B_p); the number of recorded baryons (these included identified protons and Λ hyperons, along with neutrons that suffered a secondary interaction in the chamber) was forbidden to exceed unity, baryons flying in the backward hemisphere being required to be absent among them; the effective target mass $M_t < 1.2$ GeV/ c^2 , the M_t being defined as $M_t = \sum (E_i - p_i^L)$ where the summation was performed over the energies E_i and the longitudinal momenta p_i^L (along the neutrino direction) of all recorded secondary particles. As it was shown in detail in [7, 8], the multiplicity and spectral characteristics of charged hadrons in the B_p and B_n subsamples were quite compatible with the available data obtained on hydrogen and deuterium targets.

Events which did not satisfy the aforementioned criteria were included in the subsample B_S of 'cascade' events. The numbers of accepted events of subsamples B_p , B_n and B_S were equal to 1839,

2393 and 4158, respectively. Finally, we excluded from the B_p subsample the events-candidates to the exclusive reaction $\nu p \rightarrow \mu^- p \pi^+$ (305 events, see for details [9, 10]). As it follows from the composition of the propane-freon mixture (see above), 36.7% of the subsample B_p is contributed by interactions with free hydrogen. Weighting the quasiproton events with a factor of 0.633, one can exclude the hydrogen contribution and compose a quasinucleon subsample $B_N = B_n + 0.633B_p$, corresponding to the neutrino interactions with peripheral nucleons of the target nuclei (named νN interactions), and a 'pure' nuclear subsample $B_A = B_S + B_n + 0.633B_p$, corresponding to the neutrino interactions with nucleons of the target nuclei (named νA interactions). The effective atomic weight for the nuclear subsample B_A was estimated to be approximately equal to $A_{eff} = 21$ [11].

Only in a small fraction of quasinucleon events (23.7% in νp and 16.3% in νn interactions) an identified proton ($n_p^{id} = 1$) was present. In the remaining events (with $n_p^{id} = 0$) the proton hypothesis was applied to a non-identified positively charged hadron (if any) provided that the proton hypothesis was not rejected by the momentum-range relation in the propane-freon mixture. This hypothetical proton, after introduction of a proper correction for its momentum, was combined with an accompanying positively charged hadron (an identified π^+ or a non-identified hadron) to compose a hypothetical π^+p combination. The most part of such combinations, especially in events containing two or more unidentified hadrons ($n_h^{nid} \geq 2$), is expected to be spurious due to the proton misidentification. As a result, the angular distribution of a 'proton' in the pion-'proton' rest frame turns out to be strongly shifted towards the negative values of $\cos \vartheta_p^*$, where ϑ_p^* is the angle between the 'proton' direction and the direction of the Lorentz boost from the lab system to the pion-'proton' rest system. As it has been shown by simulations [10], the $\cos \vartheta_p^*$ distribution for the case of spurious π^+p combinations is strongly peaked at $\cos \vartheta_p^* \approx -1$ and rapidly falls with increasing $\cos \vartheta_p^*$ up to $\cos \vartheta_p^* \sim -0.6$, then begins to flatten and becomes almost uniform at $\cos \vartheta_p^* > 0$. In order to reduce the share of spurious combinations in the experimental π^+p effective mass distribution for events with $n_p^{id} = 0$ and $n_h^{nid} \geq 2$, a cut $\cos \vartheta_p^* > -0.6$ was applied for the combinations of two unidentified hadrons, while those with $-0.6 < \cos \vartheta_p^* < 0$ a weight were ascribed, so that the total numbers of combinations with $\cos \vartheta_p^* < 0$ and $\cos \vartheta_p^* > 0$ (including those for events with $n_p^{id} = 1$ or $n_h^{nid} < 2$) turned out to be equal in the $\Delta^{++}(1236)$ peak region of $1.16 < m_{\pi+p} < 1.32$ GeV/ c^2 . This procedure, as it was shown in [10], enables to improve the signal to background ratio in the $\Delta^{++}(1236)$ peak region and somewhat decreases the errors in the determination of its yield. A similar weighting procedure was applied for those events of the subsample B_S which contain two or more track-candidates to the proton (composing about 75% of the subsample B_S).

3. EXPERIMENTAL RESULTS

Two different methods were applied to infer the yield of $\Delta^{++}(1232)$ in νN interactions. In the first method, a properly weighted combination of the recently measured yields [10] in νp and νn interactions, $\langle n \rangle_{\nu p}$ and $\langle n \rangle_{\nu n}$, was used. The resulted total yield, $\langle n \rangle_{\nu N}$, and the integrated yields in two ranges of the Feynman x_F variable, $x_F < 0$ and $x_F > 0$, are presented in Table 1, where the data from [10] are also shown.

In the second method, the $\Delta^{++}(1232)$ yield was inferred directly from the π^+p effective mass distributions for the B_N subsample plotted in Figure 1. Following [10] (see also [12]), the distributions are fitted by a five-parameter function

$$F(m) = C_1 \cdot BW(m) + C_2 \cdot BG(m), \quad (1)$$

where $BW(m)$ is the relativistic Breit-Wigner function [13], smeared according to the experimental resolution, while the background distribution was parametrized as

$$BG(m) = q^\alpha \cdot \exp(-\beta m^\gamma), \quad (2)$$

Table 1: The $\Delta^{++}(1232)$ yields in νp , νn , νN , νA and cascade-type interactions at three different ranges of x_F .

	νp	νn	νN (combined)	cascade subsample	νA (combined)
all x_F	0.170 ± 0.029	0.051 ± 0.012	0.087 ± 0.012	0.080 ± 0.022	0.083 ± 0.013
$x_F < 0$	0.101 ± 0.023	0.043 ± 0.011	0.061 ± 0.010	0.064 ± 0.020	0.062 ± 0.012
$x_F > 0$	0.057 ± 0.018	0.010 ± 0.009	0.024 ± 0.008	0.028 ± 0.009	0.026 ± 0.006

where q was the pion momentum in the π^+p rest frame. The results of the fit (with free parameters $C_1, C_2, \alpha, \beta, \gamma$) are shown in Figure 1 and Table 2.

Table 2: The $\Delta^{++}(1232)$ yields in νN , and νA interactions at three different ranges of x_F .

	νN	νA
all x_F	0.091 ± 0.013	0.080 ± 0.014
$x_F < 0$	0.059 ± 0.010	0.058 ± 0.013
$x_F > 0$	0.028 ± 0.009	0.029 ± 0.006

Both methods were also applied to infer the $\Delta^{++}(1232)$ yields in νA interactions. In the first method, the $\langle n \rangle_{\nu A}$ was evaluated as a properly weighted combination of yields in νp , νn and cascade-type interactions quoted in Table 1, while in the second method $\langle n \rangle_{\nu A}$ was inferred directly from the π^+p effective mass distributions for the B_A subsample plotted in Figure 1. The results of the fit by the function (1) are shown in Figure 1 and Table 2.

As it follows from Tables 1 and 2, both methods lead to practically the same results. Moreover, our data on the total and integrated over $x_F < 0$ and $x_F > 0$ regions yields do not reveal valuable nuclear effects. This statements is not, however, the case for differential yields presented below.

In the rest part of this paper, we present the results obtained with the help of the second method for the yield estimation. Figures 2 and 3 show the inclusive spectra of $\Delta^{++}(1232)$ on the x_F variable, the squared transverse momentum p_T^2 variable (p_T being defined respective to the intermediate W boson direction), the isobar total momentum p variable and the z variable – the fraction of the intermediate boson energy $\nu = E_\nu - E_\mu$ transferred to the $\Delta^{++}(1232)$ and defined as $z = (E - m_p)/\nu$, where E is the isobar total energy and m_p is the proton mass. As it is seen, the distributions on x_F , z and p in νA interactions are noticeably shifted towards lower values respective to νN interactions. This shifting can be caused by the $\Delta^{++}(1232)$ energy and longitudinal momentum losses in the nuclear medium due to both inelastic and elastic scattering on intranuclear nucleons which, according to theoretical predictions [14, 15, 16, 17, 18], might occur with cross sections compatible with (or even exceeding) the typical nucleon-nucleon cross sections. It should be noted, however, that our data on the p_T^2 -distributions (Figure 2) do not reveal significant nuclear effects: for both νN and νA interactions, the p_T^2 spectrum can be described by an exponential function with the same slope parameter $b(\nu N) = 4.2 \pm 0.7$ and $b(\nu A) = 4.3 \pm 1.1$ (GeV/c) $^{-2}$, respectively.

Further, the data on the $\Delta^{++}(1232)$ momentum distribution (plotted in Figure 3) indicate that the intranuclear absorption of $\Delta^{++}(1232)$ leading to its disappearance does not play a prominent role, otherwise one would, contrary to our data, observe a suppression of the $\Delta^{++}(1232)$ yield in νA interactions (relative to νN interactions), especially at low momentum region (e.g. $p < 1$ GeV/c), where the absorption cross section via charge-exchange reactions, such as $\Delta^{++}n \rightarrow pp$ and

$\Delta^{++}n \rightarrow \Delta^+p$, are expected to be relatively large.

Another characteristic nuclear effect is the baryon production in the kinematically forbidden region (not accessible for interactions on free nucleons), for example, the region of $x_F < -1$ or the region of $\cos \vartheta_{lab} < 0$, where ϑ_{lab} is the baryon ejection angle respective to the neutrino direction in the laboratory frame. As it can be seen from Figure 2, practically no $\Delta^{++}(1232)$ production is observed at $x_F < -1$ for νN interactions, except a faint yield at $-1.4 < x_F < 0$, reflecting the smearing of the x_F -distribution due to the Fermi-motion of the loosely bound nucleons in the target nucleus. For the case of νA interactions, the isobar yield at $x_F < 0$ is not negligible, owing mainly to the intranuclear scattering effects. Further, a possible mechanism of the $\Delta^{++}(1232)$ ejection to the backward hemisphere ($\cos \vartheta_{lab} < 0$) can be related to the pre-existence of an isobar component in the nuclear wave function [19] (see also [20] and references therein). As it follows from our data, the $\Delta^{++}(1232)$ production in the backward hemisphere (which corresponds, at our experimental conditions, to the region of $x_F < -1.4$) is negligible, the upper limit of the yield being equal to 0.01 on the 90% confidence level. This estimation can be compared with the corresponding value of 0.004 inferred in [19] from the data on (anti)neutrino-neon interactions at higher energies ($E_\nu = 10 - 200 \text{ GeV}$).

5. SUMMARY

For the first time, the inclusive neutrinoproduction of the $\Delta^{++}(1232)$ isobar from nuclei is investigated. The total yield of $\Delta^{++}(1232)$ is found to be $\langle n \rangle_{\nu A} = 0.080 \pm 0.011$, being compatible with $\langle n \rangle_{\nu N} = 0.091 \pm 0.013$ inferred for neutrino-nucleon interactions. Significant nuclear effects are observed in the $\Delta^{++}(1232)$ inclusive spectra on variables x_F , z and p , which for νA interactions turn out to be shifted towards lower values respective to those for νN interactions. This shifting can be caused by the secondary intranuclear collision processes. The p_T^2 -distributions in νN and νA interactions are found to be similar, being described with an exponential function with the slope parameter $b(\nu N) = 4.2 \pm 0.7$ and $b(\nu A) = 4.3 \pm 1.1 \text{ (GeV}/c)^{-2}$, respectively. No indication on a strong nuclear absorption of the $\Delta^{++}(1232)$, leading to its disappearance, is found. The $\Delta^{++}(1232)$ production in the backward hemisphere in the laboratory frame is found to be negligible.

ACKNOWLEDGMENTS

The activity of one of the authors (H.G.) is supported by Cooperation Agreement between DESY and YerPhI signed on December 6, 2002.

References

- [1] N.M.Agababyan *et al.*, Phys. Atom. Nucl. **74**, 229 (2011)
- [2] N.M.Agababyan *et al.*, Phys. Atom. Nucl. **70**, 1898 (2007)
- [3] N.M.Agababyan *et al.*, Phys. Atom. Nucl. **74**, 221 (2011)
- [4] V.V.Ammosov *et al.*, Fiz. Elem. Chastits At. Yadra **23**, 648 (1992)
- [5] N.M.Agababyan *et al.*, Preprint No. 1532, YerPhI (Yerevan, 1999)
- [6] N.M.Agababyan *et al.*, Yad. Fiz. **66**, 1350 (2003)
- [7] N.M.Agababyan *et al.*, Preprint No. 1578, YerPhI (Yerevan, 2002)
- [8] N.M.Agababyan *et al.*, Phys. Atom. Nucl. **74**, 246 (2011)
- [9] N.M.Agababyan *et al.*, Preprint No. 1623, YerPhI (Yerevan, 2010); arXiv:1101.2950 [hep-ex]
- [10] N.M.Agababyan *et al.*, Preprint No. 1625, YerPhI (Yerevan, 2012); arXiv:1206.4143 [nucl-ex]
- [11] N.M.Agababyan *et al.*, Yad. Fiz. **70**, 1777 (2007)
- [12] J.D.Jackson, Nuovo Cim. **34**, 1664 (1964)
- [13] M.Arneodo *et al.*, Nucl. Phys. B**264**, 739 (1986)
- [14] G.Mao *et al.*, Phys. Rev. C**53**, 2933 (1996)

- [15] T.-S. H.Lee, Phys. Rev. C**54**, 1350 (1996)
- [16] S.Boffi *et al.*, Yad. Fiz. **60**, 1320 (1997)
- [17] L.A.Kondratyuk, Yu.S.Golubeva, Yad. Fiz. **61**, 951 (1998)
- [18] G.Mao *et al.*, Phys. Rev. C**57**, 1938 (1998)
- [19] V.V.Ammosov *et al.*, Pis'ma JETP, **40**, 262 (1984)
- [20] J.Swed, Phys. Lett. **128B**, 245 (1983)

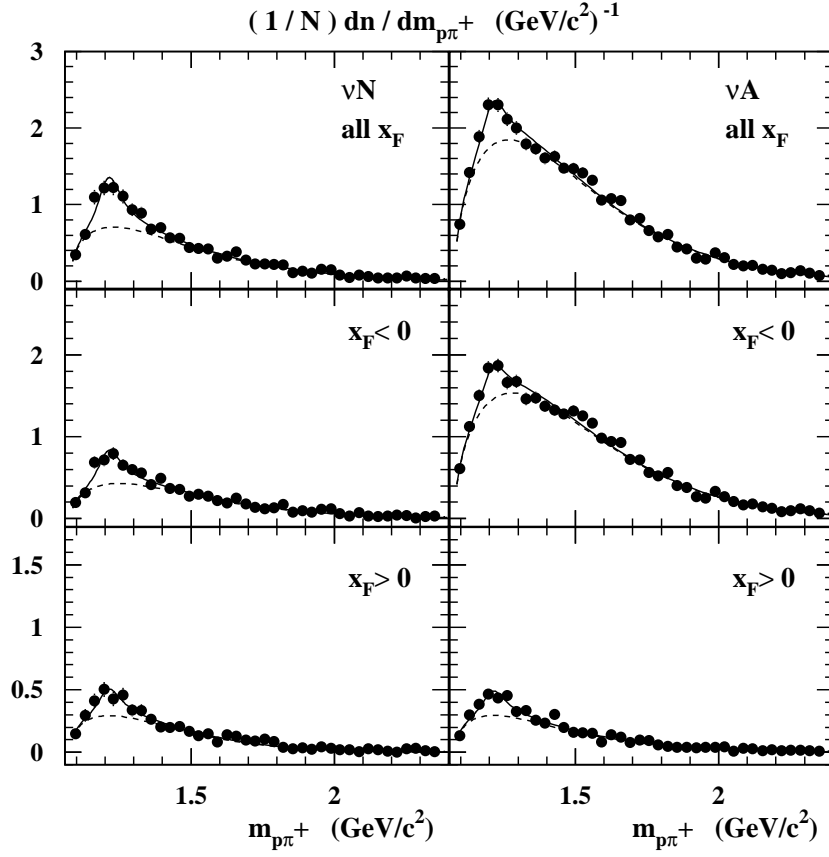


Figure 1: The $\pi^+ p$ effective mass distributions at three ranges of x_F for νN (left panel) and νA (right panel) interactions. The solid curves are the fit result, while the dashed curves corresponds to the fitted background distribution (see the text).

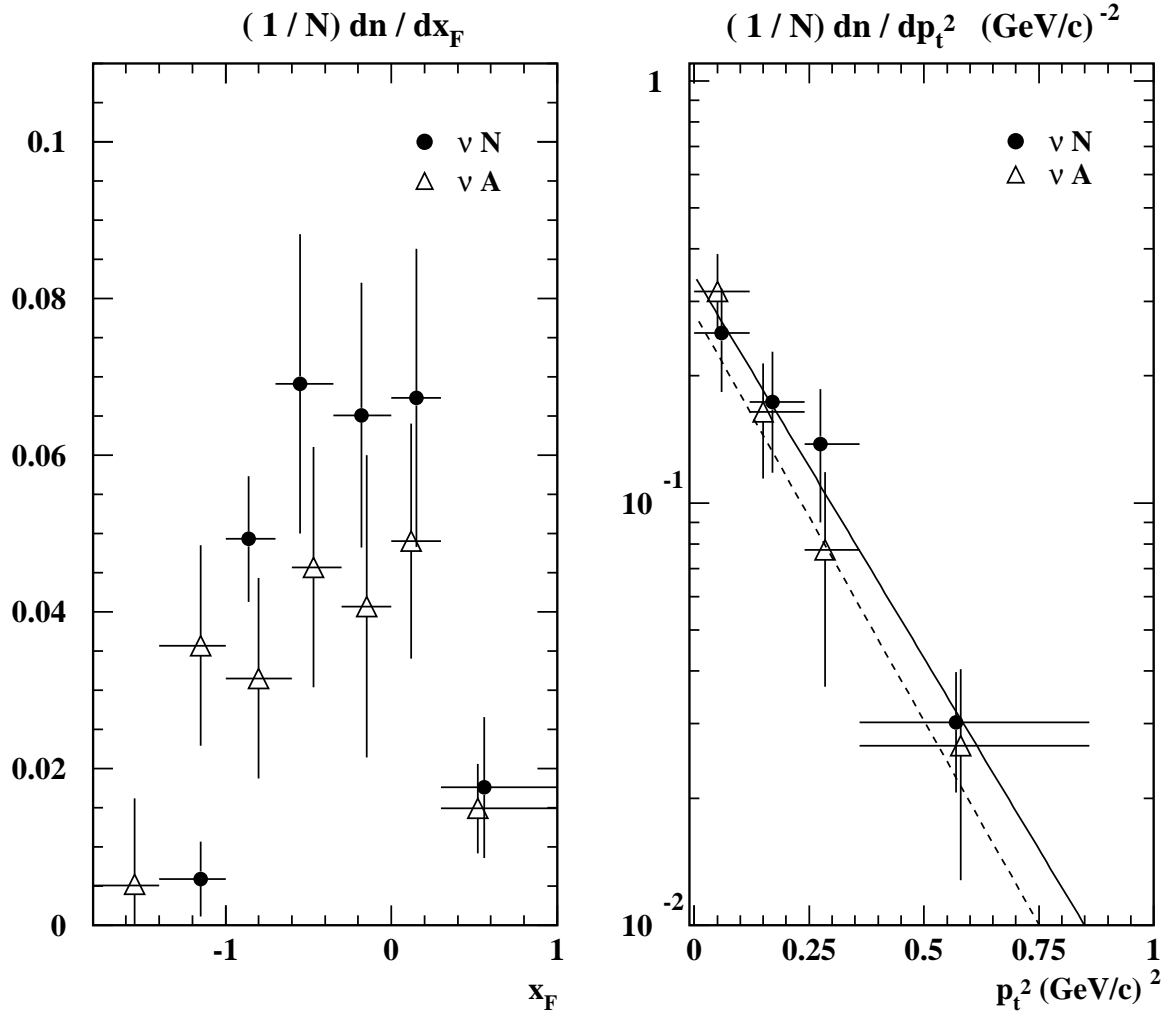


Figure 2: The $\Delta^{++}(1232)$ inclusive spectra on x_F (left) and p_T^2 (right) in νN and νA interactions. The solid (dashed) lines are the fit results for νN (νA) interactions.

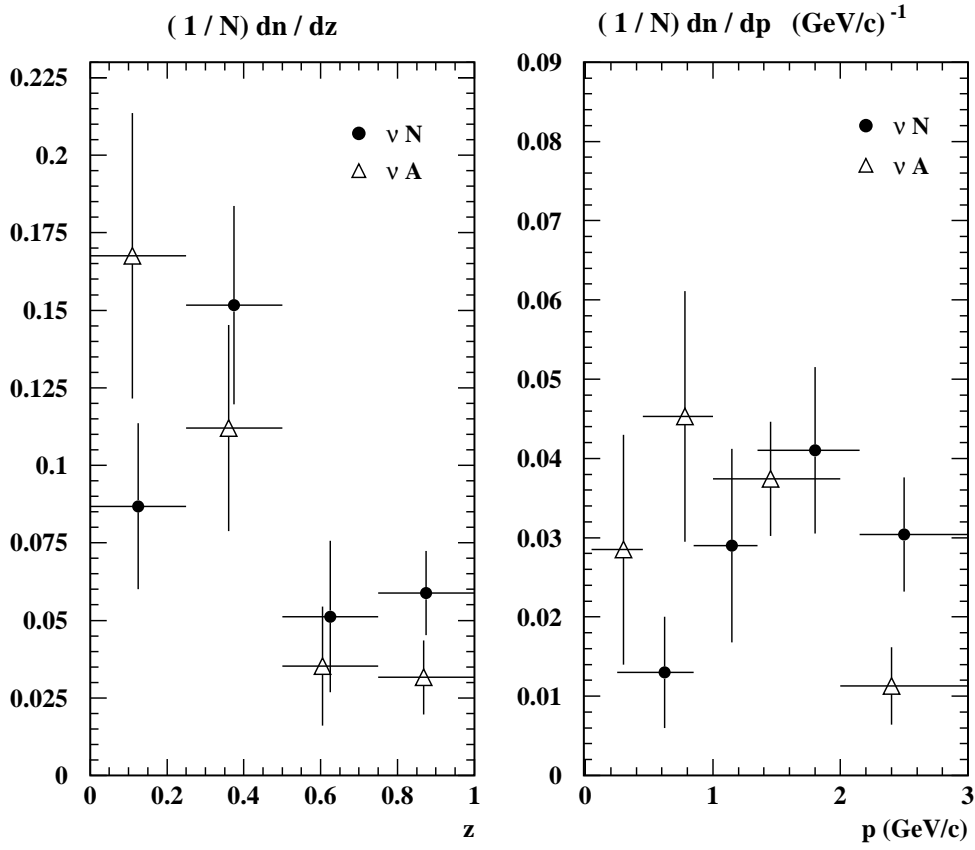


Figure 3: The $\Delta^{++}(1232)$ inclusive spectra on the z variable (left) and the total momentum (right).